Pinning and Dynamics of Magnetic Flux Moving Across the Twin Planes in YBa$_2$Cu$_3$O$_{6.97}$ Single Crystal

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We present the transport studies of field variation of the pinning force for the flux motion across the twin boundaries (TB's) in YBa$_2$Cu$_3$O$_{6.97}$ single crystals. It is found that the depinning current J_c decreases with an increase in the magnetic field due to reduction of the portion of vortex lines trapped by the TB's. However, at transport currents $J \ll J_c$, the vortex velocity weakly decreases with the increased field, i.e. it is determined mainly by the release of the vortex lines from the TB's.

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Pinning and dynamics of the flux-line-lattice (FLL) in the presence of various defect structures is a subject of long-term interest. In the YBa$_2$Cu$_3$O$_{7-\delta}$ superconductor oxygen vacancies constitute randomly distributed point-like pinning centers, while twin boundaries (TB's) constitute correlated plane-like pinning centers that are aligned along the c-axis. Though the number of twins is much smaller than that of oxygen vacancies, the pinning by TB's can be strong if vortices are aligned along the plane of twins and the Lorentz force is non-collinear to the TB's.

The magnetooptic [1, 2], transport [3, 4] and simulation [5, 6] studies have demonstrated that, in magnetic field $\mathbf{H}\|\mathbf{c}\|$TB's, the flux moves predominantly along the TB's rather than along the Lorentz force direction. This guided motion arises due to different pinning mechanisms for the vortices moving along and across the plane of twins. For the parallel motion it is governed by the presence of a random potential within the TB's, while for the perpendicular motion it is determined by suppressing the superconducting order parameter at the TB's [7]. This implies that the pinning must be much stronger for the perpendicular motion of the vortices compared with that for the parallel motion.

Single crystals were grown in a gold crucible by a self-flux method [8]. Two bridges, B1 and B2, were cut out from the crystals by a pulsed laser technique [9]. The length of the measured part of the bridges was 0.5 mm and its width was 0.2 mm. Final oxygenation of both bridges was made in an oxygen atmosphere at 400 °C for one week. The critical temperature of bridges B1 and B2 was 92.9 K and 92.7 K, respectively. The TB's inside the measured part were aligned in one direction. The distance d between the TB's was about 0.5 μm and 1 μm in the bridges B1 and B2, respectively. The transport dc-current was applied along the ab-plane, and it was parallel to the TB's in the bridge B1 and perpendicular to the TB's in the bridge B2. Measurements were performed at reduced temperature $t = T/T_c = 0.948$ in the field $\mathbf{H}\|\mathbf{c}$. Thus the Lorentz force was perpendicular to the TB's in the bridge B1, as shown in the inset of Fig. 1a, and it was parallel to the TB's in the bridge B1, as shown in the inset of Fig. 3a. The current contacts area of 2 mm^2 allowed to pass dc-current up to 1 A without overheating of the contacts.

Special attention was paid to the heating effects. The heating was estimated from the small upward deviation in the $E-J$ curves measured in the normal state, t=1.02, and in the superconducting state (t=0.98, H=15 kOe) where the $E(J)$ curves are linear in absence of the heating. The heating effects at the largest dissipation level 14 μW has been estimated to be less than 10 mK. We also looked for, but did not observe, hysteresis in the $E(J)$ curves measured with increasing and decreasing current.

Results of measurements of the bridge B1 are presented in Fig. 1. Panel (a) show the current variation in the vortex velocity $v(J) = E(J)/cB$, derived from the measured $E(J)$-curves, and panel (b) shows the current variation of differential resistance $\rho_d \equiv dE/dJ$, normalized to the flux-flow resistance $\rho_{ff} = \rho_N B/B_{c2}$ [10]. At low currents, the ratio $\rho_d/\rho_{ff} \ll 1$ corresponds to realization of the flux creep regime, and at high currents the ratio

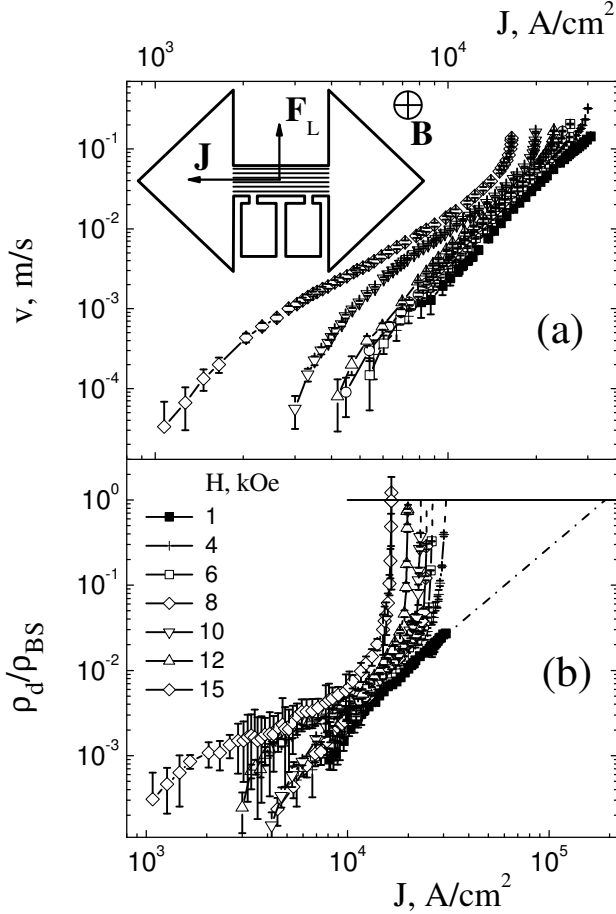*Electronic address: Aleksandr.V.Bondarenko@univer.kharkov.ua

FIG. 1: Current variation of vortex velocity (a) and differential resistance (b) for the vortex motion across the TB's. The inset shows sketch of the bridge B1 and geometry of measurements.

FIG. 2: Field variation of the depinning current J_c and of the threshold current J_v determined at vortex velocity $v = 10^{-3}$ m/s.

ρ_d/ρ_{ff} quickly approaches 1 indicating onset of the flux depinning. Extrapolating the ratio ρ_d/ρ_{ff} (which corresponds onset of the depinning) to one, as shown in the Fig. 1b by the dashed lines, we obtained the field variation of the depinning current $J_c^{\perp}(H)$ shown in Fig. 2. It is seen that the depinning current decreases with the increased field and, thus, the vortex velocity and ratio ρ_d/ρ_{ff} increases rapidly with the field when the current approaches the value of $J_c^{\perp}(H)$.

In the studied geometry, the pinning potential is heavily non-uniform along the Lorentz force action. The weak random point potential constituted by oxygen vacancies is modulated by the strong 2D potential of the TB's. In the investigated field region, 1 kOe $\leq H \leq$ 15 kOe, the intervortex distance $a_0 = (\Phi_0/B)^{1/2} = 40 \div 150$ nm is smaller compared with the intertwins separation. Therefore, the fraction of vortices trapped by the TB's, $n_{TB} \cong a_0/d$, is smaller than that of the vortices placed in between the TB's, $n_b \cong (1 - a_0/d)$. Accordingly, most of vortices are weakly pinned by point defects and the insignificant part of them is strongly pinned by the TB's.

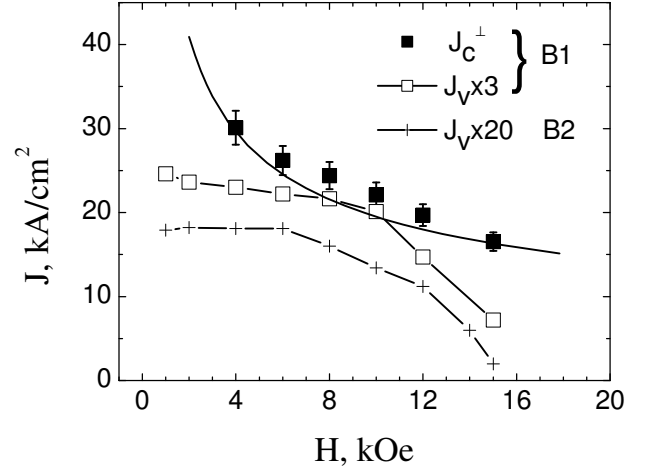In order to estimate the contribution of TB's into the total pinning force, it is necessary to know the pinning force for the vortices within the bulk of the crystal. Such information was obtained from measurements of the bridge B2. In this bridge the Lorentz force is directed along the TB's, and the pinning arises due to interaction of vortices with the random point potential. The obtained $v(J)$ and $\rho_d(J)/\rho_{ff}$ dependences are shown in Fig. 3a and in Fig. 3b, respectively. At low currents, the ratio ρ_d/ρ_{ff} is very small, but at high currents the value of ρ_d/ρ_{ff} is around unity, indicating that the measurements were performed in the flux creep and flux flow regimes. As evident from Fig. 3a in magnetic fields $H \leq$ 6kOe, the velocity v does not depend on the field within both regimes of vortex motion. The depinning current can be estimated by a conventional method, i.e. extrapolating the linear parts of $v(J)$ curves (which corresponds to the flow regime) to the zero velocity, as is shown in the inset to Fig. 3b, and by extrapolating the ratio ρ_d/ρ_{ff} (which corresponds the creep regime) to 1 (see Fig. 3b). These methods give the value of the $J_c^b \cong 2.36 \pm 0.2$ and 1.95 ± 0.2 kA/cm^2, respectively. Taking into account that final oxygenation of the bridges B1 and B2 was made under the same condition, the point pinning potentials are identical in both bridges. Thus, we can assume that the critical current due to the pinning of vortices within the bulk of the bridge B1 is about 2.2 kA/cm^2.

Assuming that the total depinning current is an additive parameter we can write

$$J_c^{\perp} \cong (1 - n_{TB})J_c^b + n_{TB}J_{TB}^{\perp} \qquad (1)$$

where $J_{TB}^{\perp}$ is the depinning current of vortices trapped by the TB's. The current $J_{TB}^{\perp}$ is determined by suppression of the superconducting order parameter at the TB's and can be written as [7]

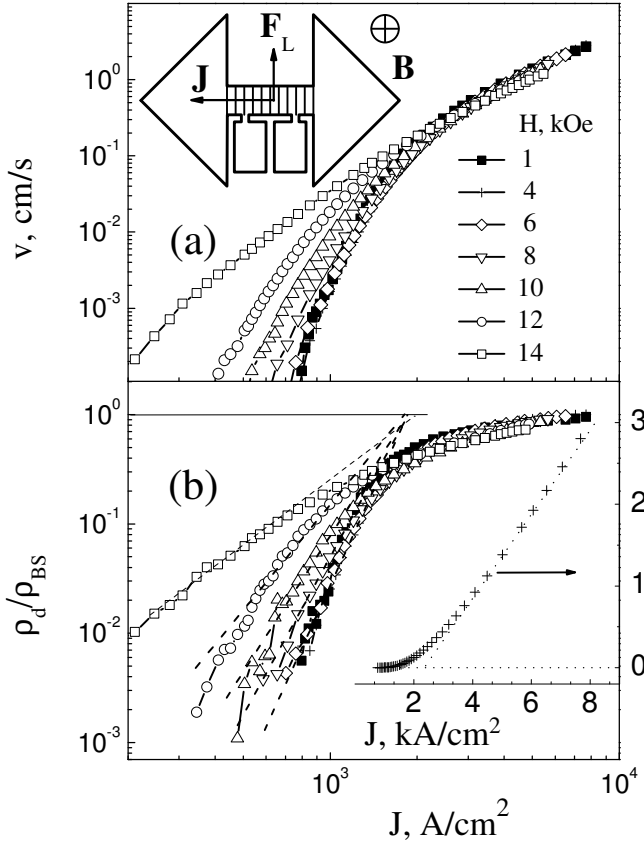$$J_{TB}^{\perp} \cong (\varepsilon_{TB}/\varepsilon_0)J_0 \qquad (2)$$

FIG. 3: Current variation of vortex velocity (a) and differential resistance (b) for the vortex motion along the TB's. The inset of panel (a) shows sketch of the bridge B2 and geometry of measurements. The inset of panel (b) shows the $v(J)$-curve for $H = 4$ kOe and a method of estimation of the depinning current J_c^b.

where $J_0 = (4/3\sqrt{3})(c\varepsilon_0/\xi\Phi_0)$ is the depairing current, $\varepsilon_0 = (\Phi_0/4\pi\lambda)^2$, and ε_{TB} is the pinning potential of the TB's. Assuming $t = 0.95$, $\lambda(t) = 400$ nm, and $\xi(t) = 6$ nm, the depairing current is estimated to be about 10^7 A/cm^2. The decoration [11], magnetooptic [12], and transport [13] experiments give the value of ratio $\varepsilon_{TB}/\varepsilon_0 = 0.017 \div 0.026$, and for reasonable ratio $\varepsilon_{TB}/\varepsilon_0 = 0.021$ we obtain the value of the current $J_{TB} = 210$ kA/cm^2. Field variation of the current J_c determined by Eq. 1 for the values of $J_c^b = 2.2$ kA/cm^2 and $J_{TB}^\perp = 210$ kA/cm^2 is shown by the solid curve in Fig. 2, and it well describes experimental data. This indicates that depinning force is really additive parameter, and decrease of the $J_c^\perp$ is caused by the reduction of fraction of vortex lines trapped by the TB's.

As is seen from Fig. 1, in magnetic fields $H \leq 10$ kOe, the thermally assisted creep across the TB's occurs at currents $J > 4$ kA/cm^2 which exceed the depinning current of the vortices placed within the bulk of the crystal. This means that the creep is controlled by the strong pinning of vortices trapped by the TB's. It should be pointed out that the vortices trapped by the TB's are

subjected not only to the action of the Lorentz force, but also to the pressure caused by the vortices placed in between the TB's because the measurement is performed at currents $J > J_c^b$. Considering that the ratio between the number of vortices placed in between the TB's and that trapped by the TB's, $(1 - n_{TB})/n_{TB}$, increases with the magnetic field, the pressure per unit trapped vortex line increases with the magnetic field too. However, as seen from Fig. 2, threshold current $J_v^\perp$, determined within the creep regime at vortex velocity criteria $v = 10^{-3}$ m/s, much weaker decreases with increased field compared to the $J_c^\perp$. This indicates that creep is mainly controlled by the release of vortex lines from the TB's potential wall, but it weak decreases with increased pressure exerted by the vortices placed in between the TB's. A possible reason of this is the high longitudinal correlation length $L_c^b = \varepsilon\xi(J_0/J_c)^{1/2}$ of the vortices within the bulk of the crystal compared with the longitudinal correlation length $L_c^{TB} = \xi(6\varepsilon_l\varepsilon_{TB}/\varepsilon_0^2)^{1/2}(J_0/J)^\mu$ of vortices trapped by the TB's [7]. Here ε is the anisotropy parameter, and $\varepsilon_l = \varepsilon_0\varepsilon^2$ is the vortex line tension in the field $\mathbf{H}\|\mathbf{c}$. Indeed, the length L_c^b is about $65\varepsilon\xi$, while the length L_c^{TB} for experimentally determined exponent $\mu \approx 0.4$ and for transport currents $J > 4kA/cm^2$ is less than $7\varepsilon\xi$. Thus, the vortices trapped by the TB's experience the external action on the length L_c^b, which is about ten times larger than L_c^{TB} and, consequently, the effect of pressure is substantially reduced.

It is important to notice difference in the flux dynamics in bridges B1 and B2. As indicated above, in bridge B2 the current variations of the ratio ρ_d/ρ_{ff}, corresponding to the creep regime, extrapolate to the value of ratio $\rho_d/\rho_{ff} = 1$ at approximately the same value of current and this value coincides within experimental error with the critical current determined within the flow regime. This indicates that for the parallel vortex motion the critical current is determined by the same kind of pinning centers, namely by the point defects. In contrast, in bridge B1 the current variations of the ratio ρ_d/ρ_{ff} corresponding to the creep regime extrapolate to the value of ratio $\rho_d/\rho_{ff} = 1$ at values of currents, which substantially exceed the depinning currents.This supports our conclusion that for perpendicular motion the depinning and creep of vortices are controlled by the different kind of the pinning centers. Besides, in the lowest of the studied field of 1 kOe, when the part of vortices trapped by the TB's is maximal, the ratio ρ_d/ρ_{ff}, corresponding to the creep regime, extrapolates to the current $190\pm20 kA/cm^2$ (see the dash-dot line in Fig. 1b), which is close the above value of $J_{TB}^\perp = 210 kA/cm^2$. This supports assumption that the current $J_c^\perp$ is really determined by Eq. 1

In conclusion, the results of transport studies of the magnetic flux dynamics for its motion across the TB's are presented. We show that the depinning current is the additive characteristic, and is determined by both pinning at the TB's and pinning by the point defects. In crystals with a small oxygen deficiency ($\delta \leq 0.03$) the transverse pinning by TB's is almost two orders of mag-

nitude larger compared with pinning by point defects. The depinning current decreases with an increased magnetic field due to the reduced portion of the vortex lines trapped by the TB's. In contrast, at temperatures not very close to the melting point of the flux-line-lattice the speed of vortex creep weak increases with the magnetic field, i.e. it is primarily controlled by the release of the vortex lines from the TB's potential wall.

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